COMPANDOR DESIGN

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COMPANDOR DESIGN

by

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PREFACE

The material for this thesis was assembled, for the most part, from experience gained in the design of a practical syllabic compandor for a modern carrier type communication system.

The design project was carried out from January 26, 1953 to April 3, 1953 at the Lenkurt Electric Company, San Carlos, California by Frank Boxall and the author. General specifications were influenced greatly by the compandor designed by the Bell Telephone Laboratories for use in the N-1 Carrier system; however, the final design was accomplished with much circuit simplification and a large reduction in the number of components with no sacrifice in performance.

The author wishes to express his appreciation to E. S. Carruthers, Engineering Coordinator, Lenkurt Electric Company for his suggestions and general supervision of the design.

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SUMMARY

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The approach taken in the recent design of a voice frequency compandor for general multichannel carrier system use is presented. Principles of operation of various types of compandors are developed mathematically. A graphical method of design of compressor and expandor variolossers using germanium diodes is discussed. Suitable matched diodes for variolosser use were obtained by a two point resistance measurement using a special series ohmeter. The control rectifiers were isolated from the signal path by inequality hybrids. A final miniaturized compandor design was built in a plug-in package of about 50 cubic inches volume. The frequency response was flat within one half db from 250 to 3500 cycles. The output level varied less than one db from the input level over an intensity range of 56 db. An effective signal to noise advantage of 22 db over a non-compressed system was obtained.

COMPANDOR DESIGN

CHAPTER I

1. Introduction:

The electrical transmission of intelligence is attended by the interesting and sometimes difficult problem of preserving the original signal in spite of physical and economic limitations in the transmitting medium. These limitations include noise, interference with other services, band-width, load carrying capacity, and many others. Because of the above limitations, alteration of the amplitude characteristics of the signal may be desirable.

2. Intensity Range:

Dynamic range of signal intensity is one of the fundamental characteristics that must be considered in the design of transmission circuits. For example the range of signal intensity in a high quality speech system is of the order of 70 decibels.[1] In order to accommodate so wide a range of intensity to certain transmission media such as multi-channel carrier and radio links, a new family of automatic devices has been developed. In general these devices contain non-linear elements whose loss or gain is a function of the signal level. A variety of control circuits are employed which may be activated by the instantaneous amplitude or envelope amplitude of the signal.

3. Intensity Range Control Devices:

Various types of signal-energy-actuated intensity range control devices are in common use. Norwine[2] devides them into the following functional groups:

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[illegible]

3. [illegible]

[illegible]

(a) Vogad - a device which will maintain at the output a signal volume which over a certain range of input is relatively independent of the speech volume applied to its input. In the ideal case, the vogad will not change its gain during periods of no speech input. Little or no alteration is made in the ratios of maximum and minimum instantaneous to average voltages of speech.

(b) Volume Limiter - a device which is a linear transducer for all speech volumes up to a critical value. Beyond this value all input volumes produce essentially the same output volume. It is essentially different from the vogad in that its gain approaches the maximum value when the input is removed.

(c) Peak Limiter - a device whose gain will be quickly reduced and slowly restored when the instantaneous peak power of the input exceeds a predetermined value. The amount of gain reduction is a function of the peak amplitude, and in practice is usually intended to be small to prevent material reduction of the range of intensity of the signal.

(d) Peak Chopper - a device which prevents transmission of peak amplitudes exceeding a critical value. An essential characteristic is that the loss it inserts is completely determined by the instantaneous voltage of the signal. Ideally the operating and release time are essentially zero.

(e) Rooter - an instantaneous compressor. Such a circuit produces an output whose instantaneous voltage is an exponential of the instantaneous voltage input.

(f) Compandor - a combination two devices - a COMpressor at the transmitting end of a circuit, and an exPANDOR at the receiving end of a circuit. The compressor reduces the dynamic range of the transmitted signal. At the receiving and the expandor restores the original dynamic range. An essential characteristic of the compressor is that it reduces the ratio of peak to average power on constant volume signal. The vogad adjusts for that volume and does not alter the ratio.

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CHAPTER II

One of the basic reasons for using compandors on carrier channels is the desirability of transmitting a wide range of speech intensities without distortion or interference from noise.

1. <u>Speech Intensity Range</u>:

Dynamic range of signal intensity is one of the fundamental characteristics of speech which must be considered in design of transmission circuits. The highest normal speech intensity determines the power handling capability which must be built into the circuit. The lowest speech intensity determines the amount of noise that can be tolerated. Lack of power handling capability will result in serious distortion of high intensity signals while excessive noise will obscure low intensity signals.

The two factors which determine the dynamic range which must be accommodated by a speech channel are the talker and the words or syllables spoken. The normal range produced by an individual talker is from 30 to 40 decibels. The total range of all speakers is about 70 decibels.

2. <u>Circuit Intensity Range</u>:

The intensity range of a circuit is the difference between the point where noise and cross-talk are equal in amplitude to the signal and the point where the signal will overload the circuit. The intensity range can be improved by reduction of noise and crosstalk and by use of amplifiers of higher power capability.

Further reduction of noise on modern transmission circuits is often uneconomic or impossible. Reduction of crosstalk between carrier systems

may require expensive line transposition work.

Increasing amplifier gain provides no improvement in cross-talk. Some improvement in signal to noise ratio is obtained though the power handling capability of the circuit must be doubled for each 3 db increase in gain.

The advantages to be gained by compressing the intensity range of signals were recognized by several early workers in the field of communications. In 1934 a compandor was successfully employed by the Bell System in a trans-Atlantic radio-telephone circuit as "an aid against static"[3]. The cost, space requirements and complexity of early compandors prevented their general use in the telephone industry until the late 1930's when the device became available for use on heavy traffic toll circuits. Rapidly expanding requirements for communication channels during World War II with attendant shortage of manpower and materials were met by employing compandors on circuits that were unusable for non-compressed carrier channels.

By utilizing recent developments in miniaturized circuit elements, low cost compandors employing only two tubes and occupying a space of less than ½ cubic foot are now being produced. Several post-war carrier systems have incorporated compandors as integral parts of the equipment.[4]

CHAPTER III

Basically the compandor is a two unit device consisting of a compressor at the transmitting end of a circuit to reduce the intensity range of transmitted signals, and an expandor at the receiving end to restore the compressed intelligence to its original intensity range. Both the compressor and expandor are non-linear devices whose gain or loss is a function of the envelope of the input signal.

Performance of a compandor is indicated by three characteristics.[1] These are (1) the control ratio, (2) the time action, and (3) the control range.

1. Control Ratio:

The control ratio determines the amount of compression or expansion of the signal. It is defined as the slope of the decibel input-output characteristic. For a compressor the control ratio must always be less than unity. Since the function of the expandor is to complement the compressor, the expandor control ratio must be the reciprocal of the compressor control ratio.

Selection of the proper control ratio for any application usually involves a compromise. Variations in level due to the transmission median will be multiplied by the expandor control ratio thus limiting the application of high control ratio expandors to closely regulated lines. While a large control ratio results in a greater theoretical signal to noise advantage, statistical studies have indicated that the maximum noise advantage obtainable is of the order of twenty two decibels regardless of the

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Selection of the proper control ratio for any application usually involves a compromise. [illegible] due to the transmission medium [illegible] by the expandor control ratio thus limiting the [illegible] [illegible] control ratio. On this basis a compressor control ratio of one half and an expandor control ratio of two provides an effective compromise.

2. <u>Time Action:</u>

The time action of the compressor determines the distortion introduced by compression of the signal. If the compressor gain were to change instantaneously with a change in input signal, the modified signal would approach a square wave as the control ratio approached zero. Transmission of this compressed signal would require a bandwidth from two to three times the bandwidth required for the original signal. A complex expandor would be required to reconstitute the signal. The control circuit of practical compandors is therefore designed to have an attack and recovery time of several milliseconds. The compressor action is hence controlled by the syllabic envelope rather than individual signal peaks. Since the envelope of a normal speech signal is of very low frequency, a normal voice channel bandwidth of 3500 cycles is adequate to accommodate a compressed signal.

3. <u>Control Range:</u>

The intensity range over which a compandor will operate properly is limited. For telephone toll circuits and Class C program circuits a dynamic range of 56 db has been determined to be satisfactory. Above and below the control range the compandor will act as a straight amplifier.

CHAPTER IV

1. Compandor Operation.

The block diagram of a typical compandor is illustrated in figure 1. A graphical picture of its action is shown in figure 2. In this particular type of compandor, the compressor output controls the loss of a nonlinear element in the transmission path; therefore the compressor is defined as backward acting. In the expandor the signal input controls the varielosser, and the expandor is termed forward acting.

2. Compandor Classes.

In general compandors can be divided into three classes:

(a) Systems introducing a variable loss element in the transmission path.

(b) Systems introducting a variable loss element in a feedback path.

(c) Systems that control the amplitude, phase or frequency of a pilot frequency which is transmitted with the signal. The pilot frequency then controls the gain or loss of the device.

Systems of the class 1 type have been most generally used in the past due to their simplicity. No discussion of the variable feedback type could be found in the literature. The tone operated system is the most versatile as well as the most complex. Since the exapndor is controlled only by a single tone, the expandor acts like an automatic channel regulator. As far as noise interference from bursts of static, instead of decreasing expandor loss, the effect is to increase expandor loss thereby reducing the

effect of the noise.

3. Backward Acting Compressor or Expandor.

A block diagram of a backward acting variolosser type compressor or expandor is illustrated in figure 3.

(a) $P_o = P_{in} - a + A$

(b) $a = f(P_o)$

(c) $P_o = P_{in} - f(P_o) + A$

P_{in} - input to variolosser in db.

P_o - amplifier output in db.

a - variolosser attenuation in db.

A - amplifier gain in db.

In an ideal system

(d) $P_o = nP_{in}$

where n is the control ratio. Let

(e) $f(P_o) = mP_o + a_o$

where a_o is the dead loss of the variolosser and is equal to A, the amplifier gain.

(f) $P_o = \frac{P_{in}}{m+1}$

(g) $m = 1/n - 1$

For a square law compressor, n is equal to ½.

(h) $a = P_o + a_o$

For a square law expandor, n is equal to 2.

(i) $a = -\frac{1}{2}P_o + a_o$

4. Forward Acting Compressor or Expandor

Figure 4 is the block diagram of a forward acting compressor or exeffect of the noise.

3. <u>Backward acting Compressor or Expander.</u>

A block diagram of a backward acting variolosser type compressor or expander is illustrated in figure 3.

(a) $P_o = P_{in} - a + A$

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P_o — amplifier output in db.

a — variolosser attenuation in db.

A — amplifier gain in db.

In an ideal system

(d) $P_o = mP_{in}$

where m is the control ratio. Let

(e) $f(P_o) = bP_o + a_o$

where a_o is the [illegible] of the variolosser and is equal to [illegible] the amplifier gain.

(f) $P_o = \frac{P_{in}}{1+b}$

(g) $b = 1/m - 1$

For a [illegible] compressor, m is equal to ½.

(h) [illegible]

For a [illegible] expander, m is equal to 2.

(i) [illegible]

4. [illegible]

[illegible]

pandor of the variolosser type. Using the same symbols as in the preceding example

(a) $P_o = P_{in} - a + A$

(b) $a = g(P_{in})$

In an ideal system

(c) $P_o = nP_{in}$

Let

(d) $a = mP_{in} + a_o$

where a_o is equal to the amplifier gain, A.

(e) $P_o = (1-m)\ P_{in}$

(f) $m = 1-n$

For a square law compressor n is equal to ½.

(g) $a = \frac{1}{2}P_{in} + a_o$

For a square law expandor n is equal to 2.

(h) $a = -P_{in} + a_o$

5. **Variable Feedback Compressor or Expandor.**

Figure 5 is a block diagram of a backward acting compressor or expandor in which the gain is varied as a function of the amplifier output by insertion of a variolosser in the feedback path.

(a) $\beta = f(E_o)$

(b) $E_o = \left[A/(1 + A\beta)\right] E_{in}$

Assume $A\beta \gg 1$.

(c) $E_o = (1/\beta)E_{in} = \left[1/f(E_o)\right] E_{in}$

Let

(d) $\beta = (1/k)\ E_o^m$

(e) $E_o = (kE_{in})^{1/m+1}$

In an ideal system

(f) $E_o = (kE_{in})^n$

(g) $m = (1/n) - 1$

For a square law compressor n is equal to $\frac{1}{2}$.

(h) $\beta = E_o/k$

For a square law expandor n is equal to 2.

(i) $\beta = \dfrac{1}{K\sqrt{E_o}}$

Similarly for a forward acting compressor or expandor of the variable feedback type (Figure 6.)

(j) $\beta = (1/k)E_{in}^m$

(k) $E_o = kE_{in}^{(1-m)}$

In an ideal system

(l) $E_o = kE_{in}^n$

(m) $m = 1-n$

For a square law compressor

(n) $\beta = (1/k)E_{in}^{\frac{1}{2}}$

For a square law expandor

(o) $\beta = 1/kE_{in}$

6. Compandor Combinations.

In an ideal system the compressor and expandor must be exact complements if the compressed signal is to be perfectly restored by the

expandor. For this reason symmetrical combinations such as a backward acting compressor and forward acting expandor are usually chosen.

CHAPTER V

1. Variolosser Design.

The word variolosser is a generic term relating to a circuit whose loss or gain is a function of a control current or voltage. Early variolossers employed the variation in amplification factor of a vacuum tube with bias. Bennett and Doba[5] showed that a linear control current relation to output or input combined with the exponential characteristic of a typical varistor such as copper oxide and germanium diodes is particularly favorable to compression or expansion with a control ratio of one-half. For reasons of space, simplicity, and efficiency the germanium diode is probably the most desirable non-linear element for modern miniaturized compandor design.

2. Germanium Diode Characteristics.

The static characteristic of a typical germanium diode is plotted in Figure 7. This characteristic may be approximated by $I = kE^n$. In variolosser operation, the variation in dynamic resistance of the diode with bias current controls the variolosser attenuation.

$$r = dE/dI$$

$$I = kE^n$$

$$r = R/n$$

where r is the AC resistance of the diode and R is the DC resistance of the diode evaluated at a particular bias current. Plots of DC resistance R vs. DC bias current I on logarithmic paper for several similar types of diodes indicated that the characteristics were essentially linear but

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r = [illegible]

I [illegible]

r [illegible]

[illegible]

varied in magnitude and slope. The direct current resistance of a diode at low bias currents can be measured to one percent in a symmetrical Wheatstone bridge.

3. Variolosser Configuration.

The simplest form of attenuator is the L type. In a compandor the bias current supplied to the non-linear element will vary with the envelope of the input signal; therefore, a balanced form of the L attenuator must be used to prevent unintentional modulation of the signal by AC components of the control bias. This imposes rather severe requirements on the matching of the diodes.

Theoretically the signal voltage drop across each variolosser diode should be small compared to the DC voltage drop to limit the distortion introduced by the non-linearity of the diode characteristic. In a balanced circuit the second harmonic distortion will cancel. Preliminary measurements indicated that the third harmonic would be more than 40db below the fundamental if the peak to peak signal voltage was limited to one-half the DC voltage.

In the Lenkurt compandor a 28 db range of attenuation was required in both the compressor and expandor variolossers. A two section balanced L type attenuator was found to be necessary to cover this range.

4. Design Procedure.

The mathematical analysis of two terminal varistor variolossers by Bennett and Doba[5] imposed simplifying conditions that were not compatible with the problem at hand. The mathematical approach was therefore abandoned in favor of a graphical method.

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[illegible]

[illegible]

The bias current, I_{DC}, was selected as a parameter. Curves of load current vs. power input in dbm for a full wave rectifier with condenser input were determined experimentally for various resistance loads in series with a diode to simulate the load presented by a variolosser. Increase in diode resistance with decrease in current, decrease in rectifier efficiency with decrease in current, and variation of mismatch between generator internal impedance and equivalent load resistance resulted in varying departure from linearity over the input range. By comparison of these power vs. current curves with computed attenuation vs. current curves of a two section L attenuator, curvature of the attenuator characteristic at low bias currents could be made to balance the curvature of the power curve, when the diodes were used as shunt attenuator elements.

5. Compressor Variolosser.

By the methods outlined in section 4, approximate component values were selected. An input transformer turns ratio was specified to reflect a nominal impedance of 600 ohms to the primary. A series of experimental curves of attenuation vs. power input were then run using the circuit of figure 8. Measured characteristics deviating less than one db from the ideal were obtained.

6. Expandor Variolosser.

The expandor variolosser was designed to be the inverse of the compressor variolosser. A two section balanced L type attenuator was used with the diodes as series element. Comparison of control rectifier power vs. current curves with computed attenuation vs. current curves of the attenuator indicated the curvature of the attenuator characteristic at

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5. Compressor Linearity.

By the methods outlined in section 4, appropriate component values were selected, the input transformer turns ratio was specified to reflect a matched impedance of 600 ohms to the triode. A series of experimental curves of attenuation vs. power input were then run using the circuit of [illegible], to obtain characteristics deviating less than [illegible] from the ideal [illegible] relations.

6. [illegible]

[illegible]

low current values would not be compensated for by curvature of the power vs. current characteristic. By empirical methods the circuit of figure 9 was devised. Since the attenuation was increasing too rapidly at low bias current values, the logical solution was a fixed resistor shunt around the series diodes. Computation of the value of this shunt was not attempted due to complex characteristic of a non-linear element shunted by a linear resistance. Attenuation vs. power input characteristics varying less than one db were obtained. By fortunate coincidence the deviation of the compressor and expandor characteristics from the ideal tended to cancel at high signal levels thereby resulting in a superior system characteristic.

7. Diode Selection.

As is well known present production runs of germanium diodes vary widely in characteristics. For successful mass production of varielossers a rapid method of selecting matched diode quads is necessary.

As has been shown in section 2, the dynamic resistance of an idealized diode is a constant times the static resistance of the diode at a specified value of bias current. Since the problem of diode selection is primarly one of grouping diodes of matched characteristics rather than precise determination of their characteristics, a selection process based on measurement of DC resistance was decided upon.

The most simple and accurate way of measuring DC resistance of a diode is with a symmetrical Wheatstone Bridge. The power source for the bridge may be a 45 volt "B" battery with adjustable series resistance to limit the current flowing thru the bridge to twice the desired bias current. Since the low current values would not be compensated for by curvature of the power vs. current characteristic. By empirical methods the circuit of Figure 9 was devised. Since the attenuation was increasing too rapidly at low bias current values, the logical solution was a fixed resistor shunt around the series diodes. Computation of the value of this shunt was not attempted due to complex characteristic of a non-linear element shunted by a linear resistance. Attenuation vs. power input characteristics varying less than one db were obtained. By fortunate coincidence the deviation of the compressor and expander characteristics from the ideal tended to cancel at high signal levels thereby resulting in a superior system characteristic.

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[illegible]

resistance measurements are made at 500 micro-amperes and 10 micro-amperes diode current, the combination of a high voltage battery and a high series resistor is approximately a constant current source. Due to symmetry of the bridge the current will divide equally between the two arms of the bridge.

Although the bridge method is satisfactory for laboratory use, a more rapid method is required for production testing. For reasons of economy, an operator with no technical training should be able to group several thousand diodes daily. With this requirement in mind a specialized series type ohmmeter was assembled. From knowledge of actual diode resistance measured by the bridge method equivalent battery voltage and series dropping resistance were selected to give a mean diode current of 500 micro-amperes. The meter scale was then blocked off into eight 10 micro-ampere sections lettered A thru H. A similar ohmmeter was assembled to give a mean current of 10 micro-amperes with the meter scale blocked off into eight 0.2 micro-ampere sections lettered A thru H. Actual plots of some thirty diode characteristics indicated that a two point selection scheme would be adequate.

The diodes were then divided into eight groups on the basis of their resistance at 500 micro-amperes. Each group obtained was then divided into eight sub-groups on the basis of their resistance at 10 micro-ampere resistance. The end result was sixty-four possible diode groups identified by rectangular coordinates; i.e. AB, CC, etc. The adequacy of the system was checked by successful operation of diodes so selected in compandor variolossers.

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CHAPTER VI

1. Control Rectifier Design:

Basically the control rectifier is an envelope detector. The most important design characteristics are the attack time and the recovery time. Attack time is determined primarily by the equivalent source resistance of the signal circuit driving the rectifier. Previous experience has indicated that an attack time of from 5 to 20 milliseconds is satisfactory.[6] The complex envelope of speech makes the precise determination of optimum attack time impossible. An indication of a suitable value can only be made on the basis of listening tests made by experienced telephone engineers.

Suitable values for recovery time have been determined by listening tests to be of the order of 100 milliseconds.[6] Too short values of recovery time result in "thump" as the compressor variolosser reduces loss rapidly at the end of a speech burst. The optimum value can only be determined by extensive listening tests by skilled personnel.

2. Rectifier Filter Circuit:

The simplest circuit which will meet the above timing specifications is a shunt capacitor followed by a series resistor. Ideally the series resistor should be large in comparison with the static resistance of the variolosser in order that the variolosser bias current will be a linear function of the input voltage. In practical circuit design this characteristic must be compromised due to limitation in available driving voltage. Some control over the output current versus input power to the

rectifier is possible by specification of the rectifier transformer turns ratio.

The equivalent load impedance presented at the primary of the rectifier input transformer is meangingless due to the complex waveform produced by the non-linear rectifier elements. An experimental determination of maximum power transfer using a 1000 cycle source indicated that for a load of given resistance, maximum power will be delivered to the load when the equivalent generator impedance at 1000 cycles is of the order of the load resistance. If a center-tapped full wave rectifier transformer is used, allowance must be made for the fact that only half of the transformer is active at any one instant.

By use of the above principles rectifier transformers were specified for maximum efficiency by matching the generator resistance to the vario-losser load at maximum bias current values. Due to curvature of the power transfer characteristic a desirable low ratio of maximum to minimum bias current was also obtained over the control range of the compandor.

3. <u>Rectifier Isolation</u>:

As is well known, the input to a full wave rectifier with condenser input filter is rich in odd order harmonics. In a compandor design some method of isolating the signal path from this rectifier distortion must be provided. An excellent system is the use of an isolating control rectifier.[4] To facilitate miniaturization, the Lenkurt compandor employs a hybrid junction for isolation purposes. Attenuation of the third harmonic distortion components to 50 db below the fundamental were obtainable rectifier is possible by specification of the rectifier transformer turns ratio.

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7. Rectifier Filter:

[illegible]

by this method with a considerable saving in the number of components.

4. Transformer and Resistance Hybrid Junctions.

The literature contains very few references to hybrids although they are extensively used in the telephone industry. In recent years the principle has been extended to microwave frequencies. Basically the hybrid can be represented as an eight terminal network. (Figure 10) When driven from any pair of terminals, power will be transmitted to the two adjacent pairs of terminals but not to the opposite pair of terminals. The network may be designed for a specified division of power between the two transmission paths. This characteristic is particularly desirable in compandor design as the greater portion of power can be transmitted to the control rectifier. Since the variolosser must be operated at a low level for minimum distortion, the resultant attenuation in the signal path is compatible with the design requirements.

The hybrid is a bilateral device and must be terminated in its characteristic impedance at both sending and receiving ends to prevent reflection of power. In the case of a forward acting compressor or expandor the driving circuit impedance may not always be under the control of the designer. For example, in the Lenkurt 45A System the expandor was driven from a low pass voice frequency filter. In the range from 250 cycles to 3500 cycles the filter was designed to present an equivalent source impedance of 600 ohms to match in the expandor input. Outside this band the equivalent source impedance would approach zero or infinity depending on the particular filter configuration. Since the control rectifier generates by this method with a considerable saving in the number of components.

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The [illegible] devices [illegible] terminated in its characteristic impedance at both sending and receiving end to prevent re-flection of power. [illegible] an appreciable third harmonic, this harmonic will lie outside the filter pass band. This harmonic will be transmitted back to the source and reflected from the source into the signal path. To attenuate this harmonic to an acceptable level a resistance hybrid was employed with a loss of 8 db in the rectifier transmission path. The 8 db value was determined experimentally using a signal source of low impedance to provide a reflection coefficient at the generator of approximately one.

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CHAPTER VII

1. Amplifier Design:

The amplifiers in the compandor are of conventional design. For reasons of reliability and ease of maintenance, tube types in the 45A system were limited to the 6AK5 pentode and Western Electric 2C51 twin triode. To obtain the required gain of 50 db for the compressor amplifier a two stage transformer coupled amplifier using a 2C51 was used. In the expandor amplifier resistance-capacitance interstage coupling was used as a gain of only 40 db was required. Miniaturized transformers measuring three quarters of an inch on a side were specially designed for the compandor. Further savings in space were made by reducing the design to the minimum number of parts. Cathode bypass capacitors were eliminated by using small cathode resistors to reduce the degeneration and obtaining the required operating bias by a voltage divider from the plate supply. The use of printed circuits was studied but rejected due to wide tolerance of available printed components. To meet production specifications, components of 5% tolerance were required.

2. Use of Negative Feedback:

To insure that the amplifier gain would remain within acceptable limits with aging of tubes and components a minimum of 14 db of overall feedback was specified. A combination of current and voltage feedback was used to adjust the amplifier output impedance to exactly 600 ohms. Matching of impedances for maximum power tranfer is common practice in carrier systems. Use of a large value of overall feedback made the use of miniature trans-

CHAPTER VII

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2. Use of Negative Feedback:

To [illegible] amplifier [illegible] within acceptable limits [illegible] overall feedback [illegible] modulation of [illegible] [illegible] formers possible while maintaining the amplifier response flat within one half db over the voice frequency range of 250 to 3500 cycles.

CHAPTER VIII

1. <u>Steady State Testing Techniques:</u>

In preliminary testing of the compandor a high quality sine wave generator was used as a signal source. According to design specifications, the compressor and expandor control ratios shall not vary more than plus or minus one half db from the ideal over the control range of 58 db. The overall system characteristic shall be flat within one db over the same range. The system frequency response shall be flat within one half db over the range from 250 to 3500 cycles. Harmonic distortion components shall be at least 40 db below the fundamental. All measurements are to be accurate to within 0.1 db.

To obtain measurements of satisfactory accuracy, precision decade attenuators calibrated in 0.1 db steps were used in conjunction with a Hewlett Packard 400C AC vacuum tube voltmeter as a balance indicator. Harmonic distortion measurements were made with a wave analyzer.

2. <u>Dynamic Testing Techniques:</u>

Actual operation of the compandor is more a function of the system transient response than its steady state response. Determination of satisfactory operation of the compandor was made by actual listening tests. Repetitive phrases from a closed loop on a tape recorder were used as a test signal. By means of an "A-B" test panel, the operator could switch from a compandor channel to a conventional channel. From two to four compandors were connected in tandem to magnify any inherent faults. To minimize the human element the two transmission channels were identified to the operator only

as Channel A and Channel B. When a number of experienced telephone engineers could not consistently identify the companded channel, the operation of the compandor was considered satisfactory.

Measurement of actual noise advantage is made in a similar qualitative manner. A noise source is introduced into the compressed section of the compandor transmission path. A similar noise source in the conventional path is then adjusted by the operator until he estimates it to be of the same level as the noise in the compandor path. The observations of a group of at least twenty five operators are then averaged. A compandor noise advantage of about 22 db was established by the Bell Telephone Laboratories with this method[1].

CHAPTER IX

1. Benefits of the Compandor:

Theoretically the use of compandors of high control ratio would provide large noise advantage on transmission circuits. For a square law compandor the advantage would be equal to the maximum compressor gain or 28 db. Since the operation with complex signal input deviates from the ideal steady state since wave input, actual noise advantage has been found to be of the order of 22 db regardless of control ratio.

Due to the noise reduction many channels unsuited for conventional operation become usable with the application of compandors. For example lines transposed for carrier frequencies up to 35 kc ordinarily need reworking to prevent objectionable cross talk if higher frequency carrier systems are added. In practice these lines have been found usable with high frequency carrier systems employing compandors. For the same reasons voice frequency lines are often suitable for carrier frequencies up to 35 kc with a compandor system.

2. Application of Compandors to Radio Circuits:

Multi-channel radio links using compandors with the carrier equipment can have lower fading margins, longer transmission paths, and greater number of repeaters because of the addition signal to noise advantage of the compandor. In convential amplitude modulated or single sideband radio transmitters an appreciable increase in equivalent power can be achieved due to the decreased ratio of peak to average power in compressed speech.

CHAPTER IX

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Due to the noise reduction many channels [illegible] for conventional operation [illegible] with [illegible] of compandors. [illegible] lines [illegible] working [illegible] carrier systems [illegible] high frequency [illegible] for the same [illegible] some [illegible] carrier frequencies [illegible] system.

2. Limitation of [illegible]:

[illegible]

3. <u>Savings in Manufacturing Costs:</u>

Substantial savings can often be made in manufacturing costs when carrier systems are designed with integral compandors. Design specifications of line filters, channel filters, and directional hybrids can often be relaxed. Repeater spacing may also be increased.

4. <u>Compandor Applications:</u>

Past applications of compandors have been limited to telephone circuits and a few long distance radio links. Suggested military applications are ship to ship, ship to shore, and ship to airplane VHF voice circuits. A suitable compandor operating over a limited video band would improve the performance of radar telemetering relay links. Intelligent use of compandors may assist materially in solving present overcrowding of available communication channels.

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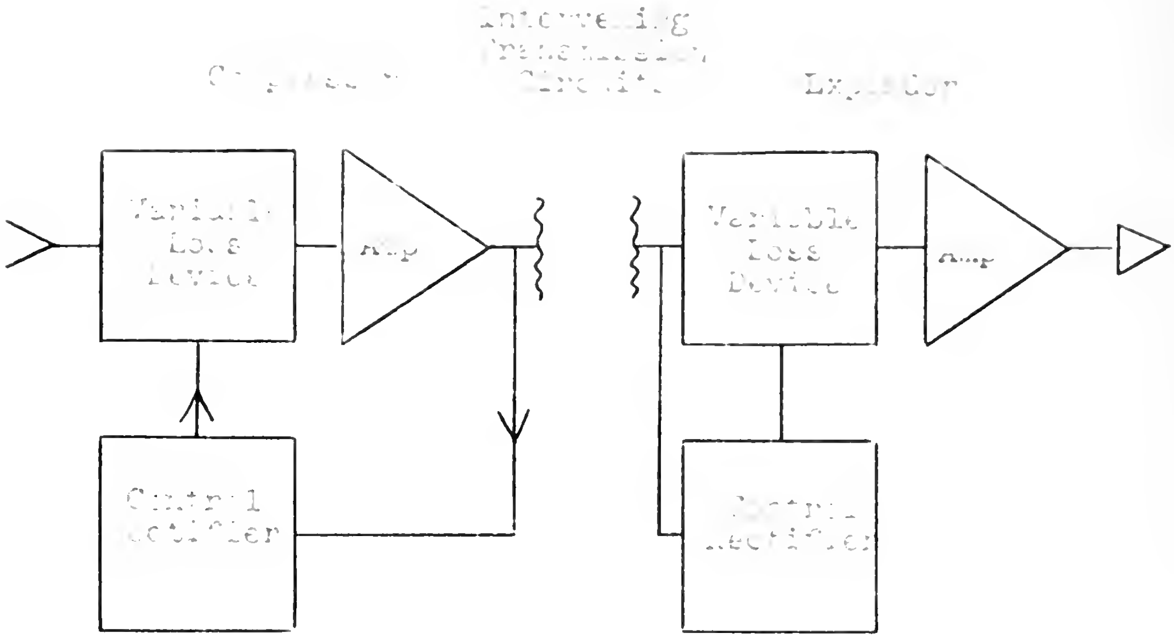
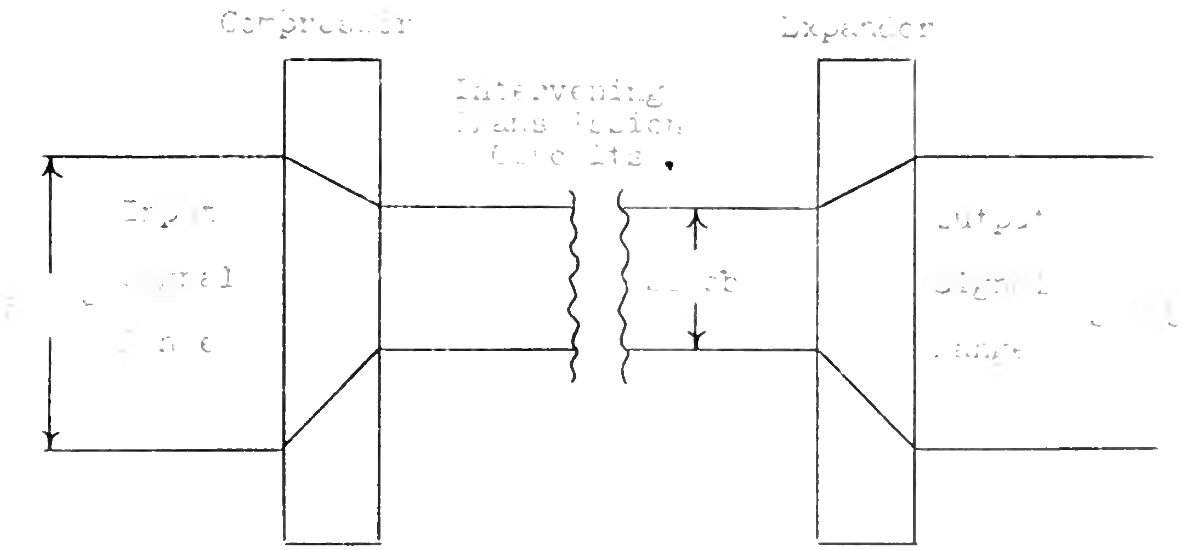


Figure 1. [illegible] expander consist of a variable loss device, an amplifier, and a control rectifier.



[illegible] restored [illegible]

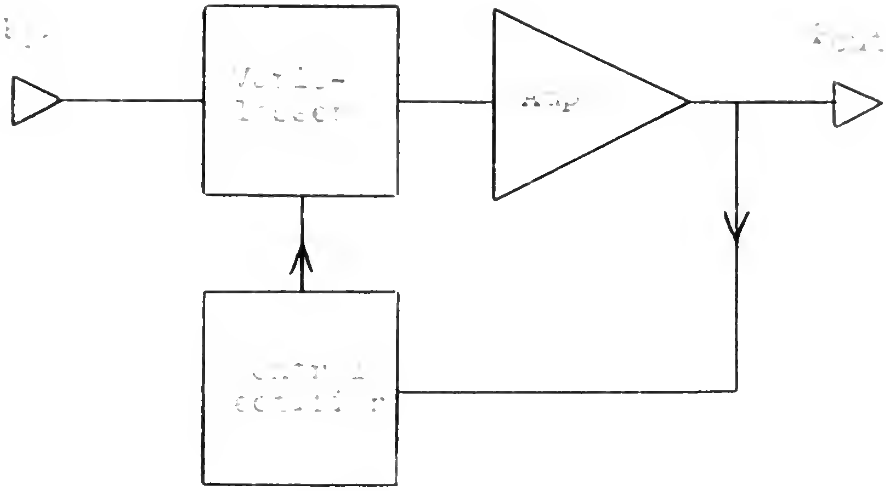


Figure 6. Block diagram of backward acting compressor or expander.

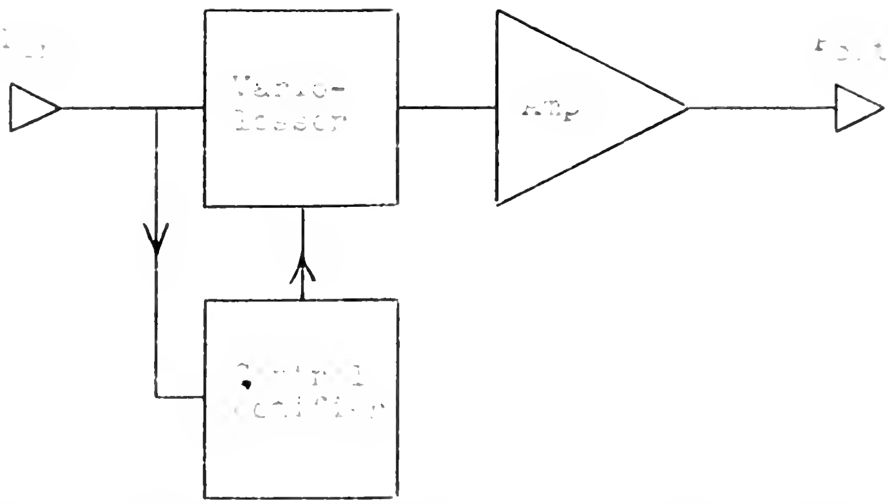


Figure [illegible]. Block diagram [illegible] acting compressor [illegible]

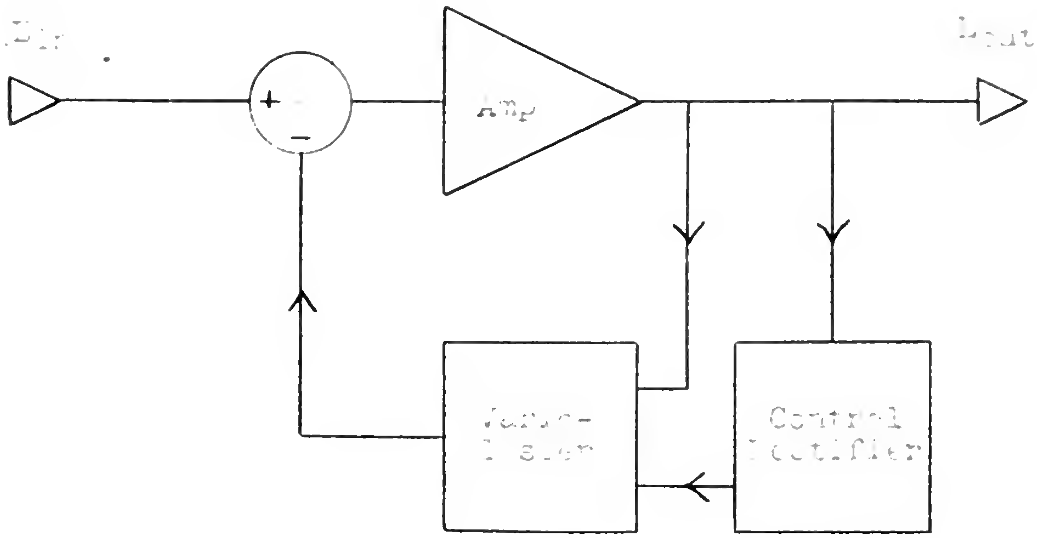
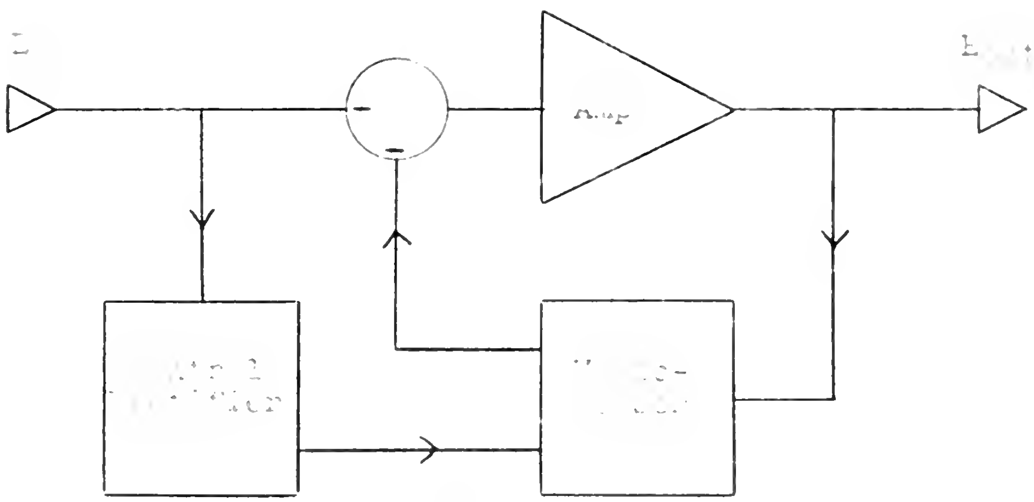


Figure 5. Block diagram of variable feedback backward acting compressor or expander.



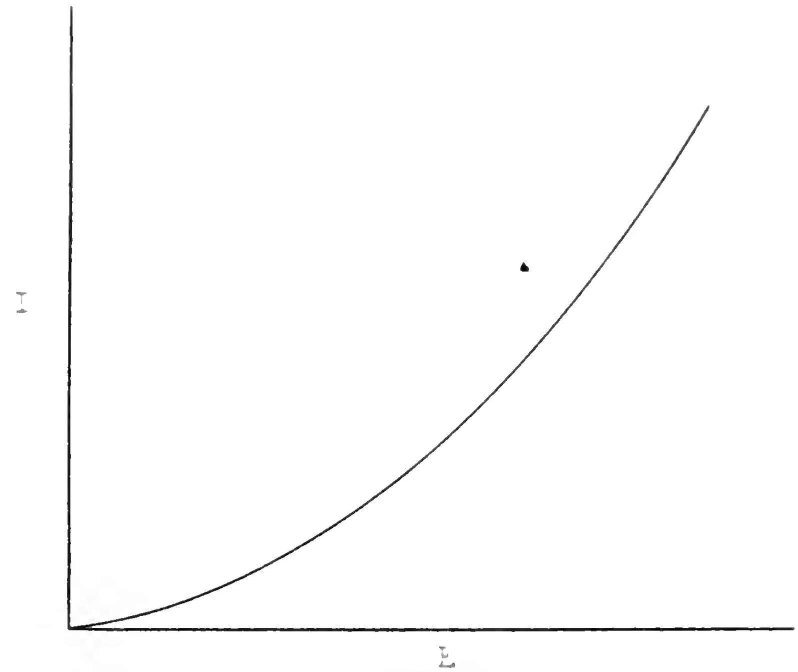
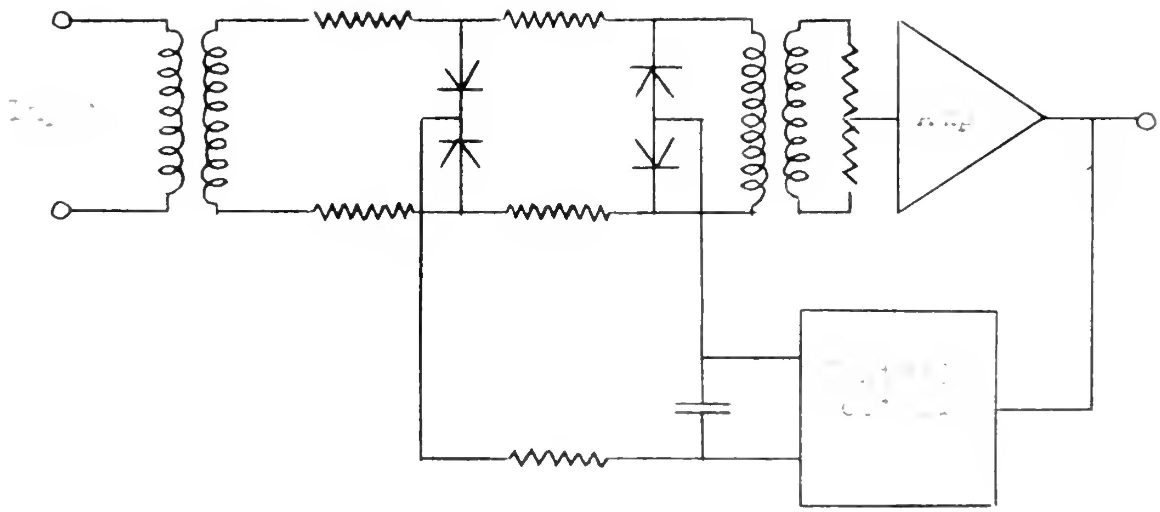


Figure 7. Static characteristic [illegible]



[illegible]

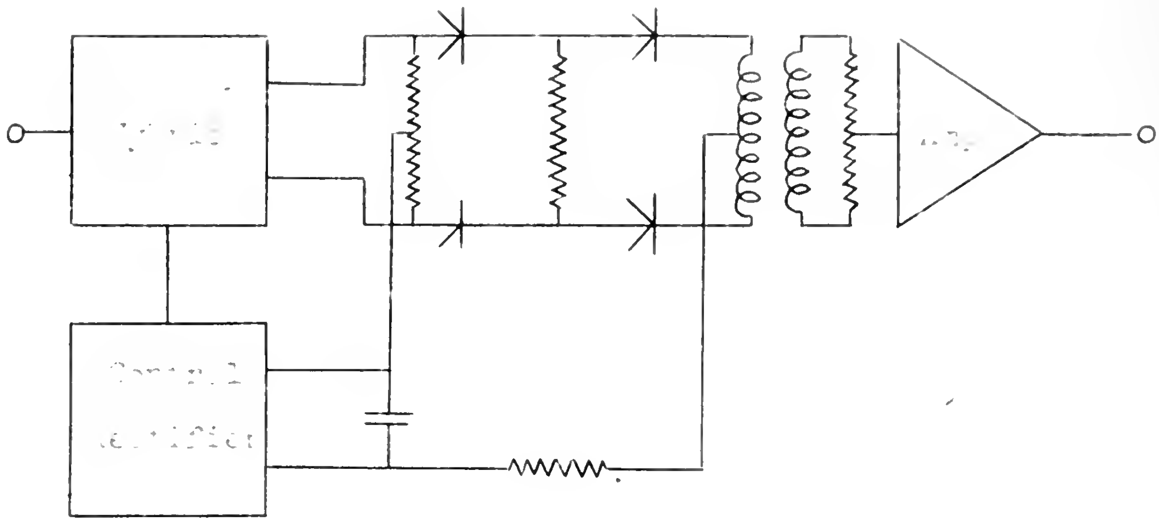
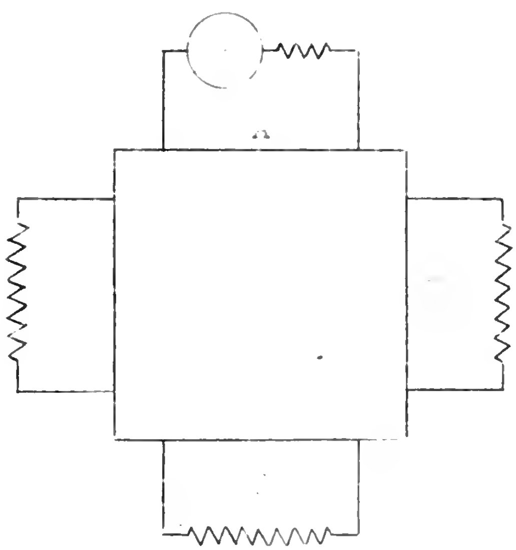


Figure 9. [illegible]



[illegible]

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